Black-hole microstate spectroscopy: ringdown, quasinormal modes, and echoes

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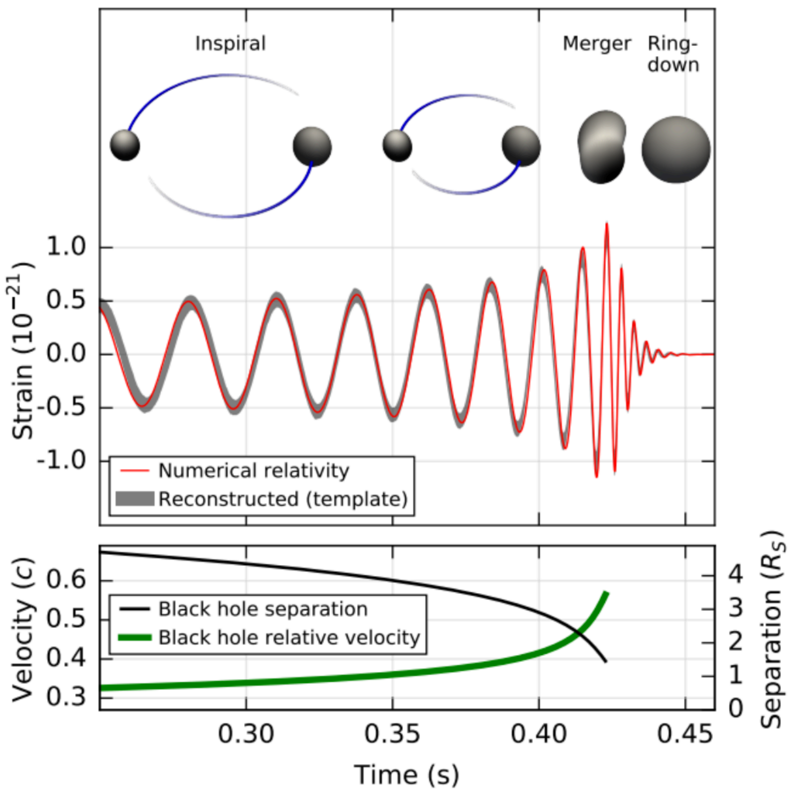
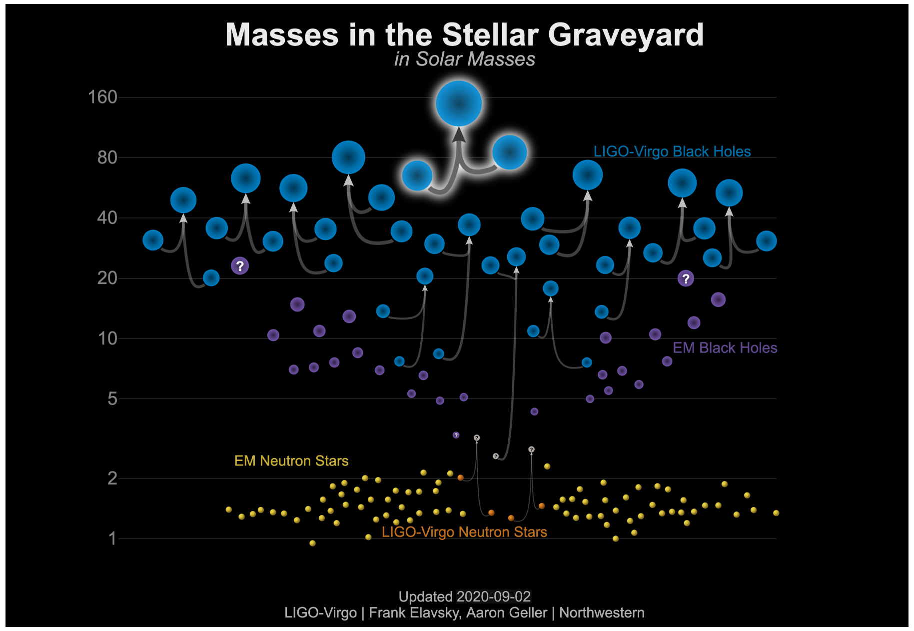
Gravitational wave astronomy



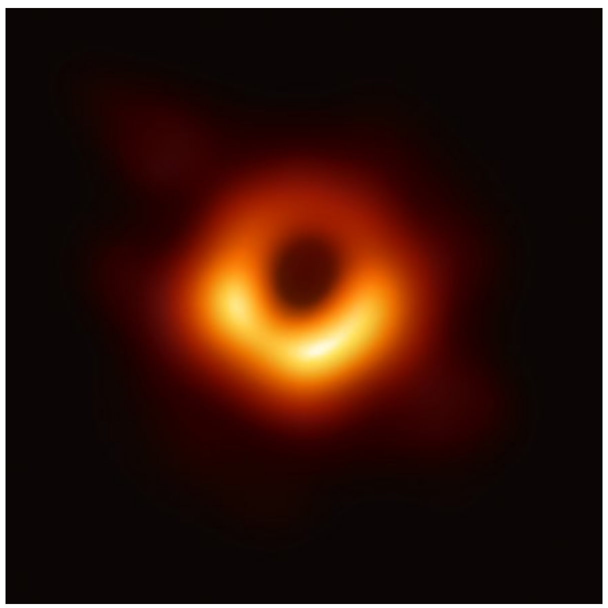


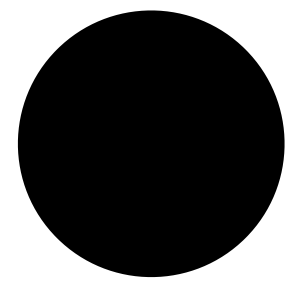
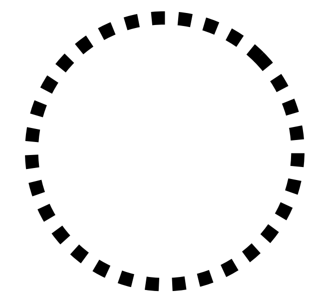
- What we can learn from gravitational waves.
  - Origin of black holes/ binaries, Primordial black hole, equation of state of neutron star, BH as a particle detector, Test of gravitational theory, et al

Exotic compact object

Q. Can we distinguish BH from exotic compact object using gravitational waves ?

$\longrightarrow$ Test of general relativity



is  or  ?

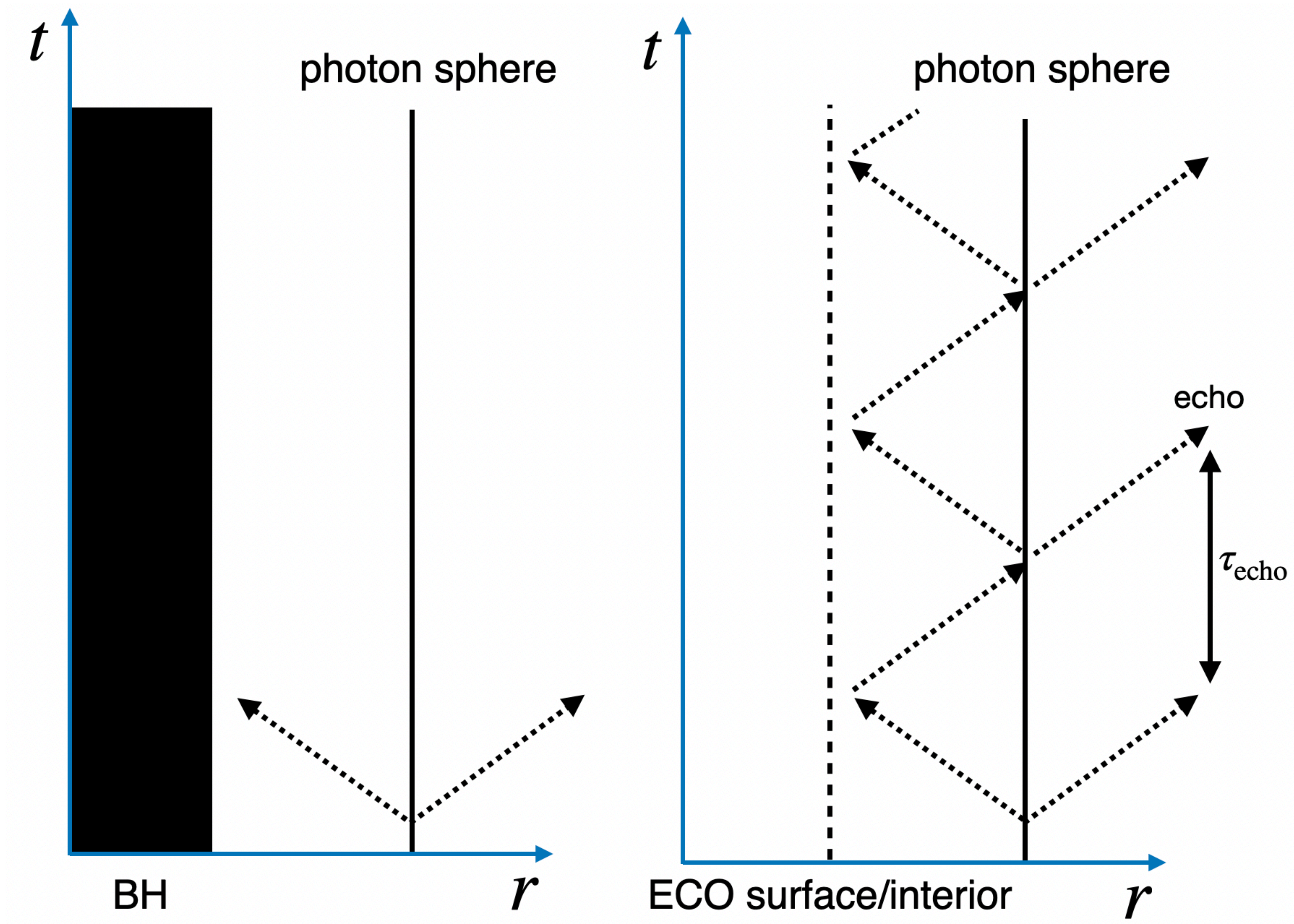
BH ECO

- Exotic compact object (ECO)
  - Boson stars, gravastars, wormholes, firewalls, Fuzzballs et al.
  - Important paramers
    - Compactness : C $\quad C_{\rm BH} = 1$ $\quad$ cf: $C = \dfrac{2M}{R}$
    - Reflectivity : $\mathscr{R}$ $\quad \mathscr{R}_{\rm BH} = 0$

Black hole vs ECO

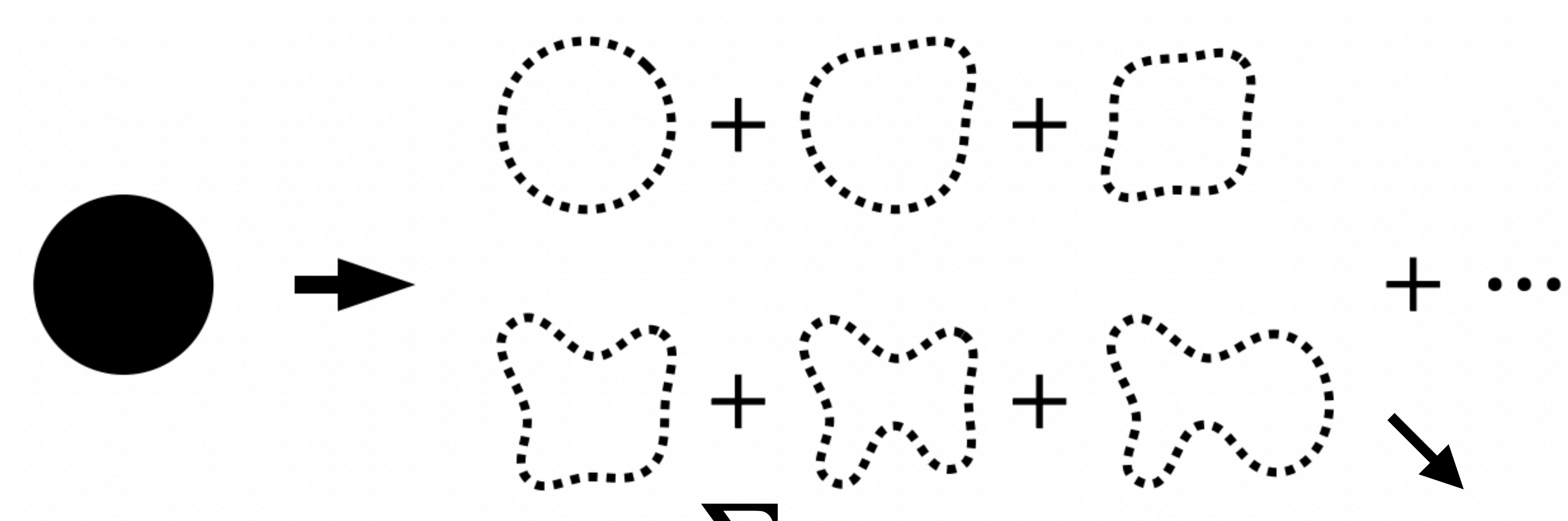
$C > 2/3$

- If ECO is enough compact, it can have the photon sphere.
- General properties of gravitational waves from BH and ECO



Fuzzball proposal

- BHs in GR have many theoretical problem.
  - How to describe the BH singularity.
  - Information paradox ?
  - What is the origin of the BH entropy ? et al
- String theory provides horizon-scale microstructure that replaces the black hole. (Fuzzball proposal)



$|\mathrm{BH}>$

- BH horizon
- curvature singularity

$\sum |\mathrm{microstate}>$

BH entropy

- horizonless
- smooth (no singularities in 5-dim)
- same charge as corresponding BH

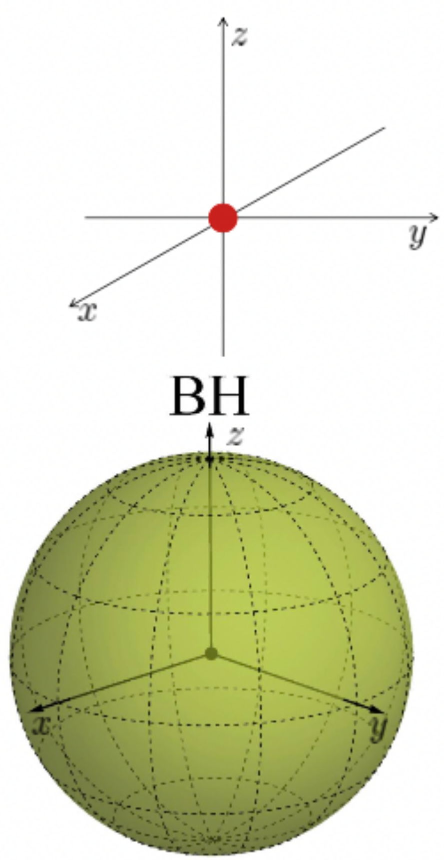
Fuzzball proposal

- We focus on the microstate geometry corresponding to 4-charge BH with 3 electric and 1 magnetic charge. M.Bianch et.al (2017)

4 charge BH

$$ds^2 = -f(r)dt^2 + f(r)^{-1}\delta_{ij}dx^i dx^j$$

$$f(r) = \left(H_1 H_2 H_3 H_4\right)^{-1/2} \qquad H_A = 1 + \frac{Q_A}{r}$$

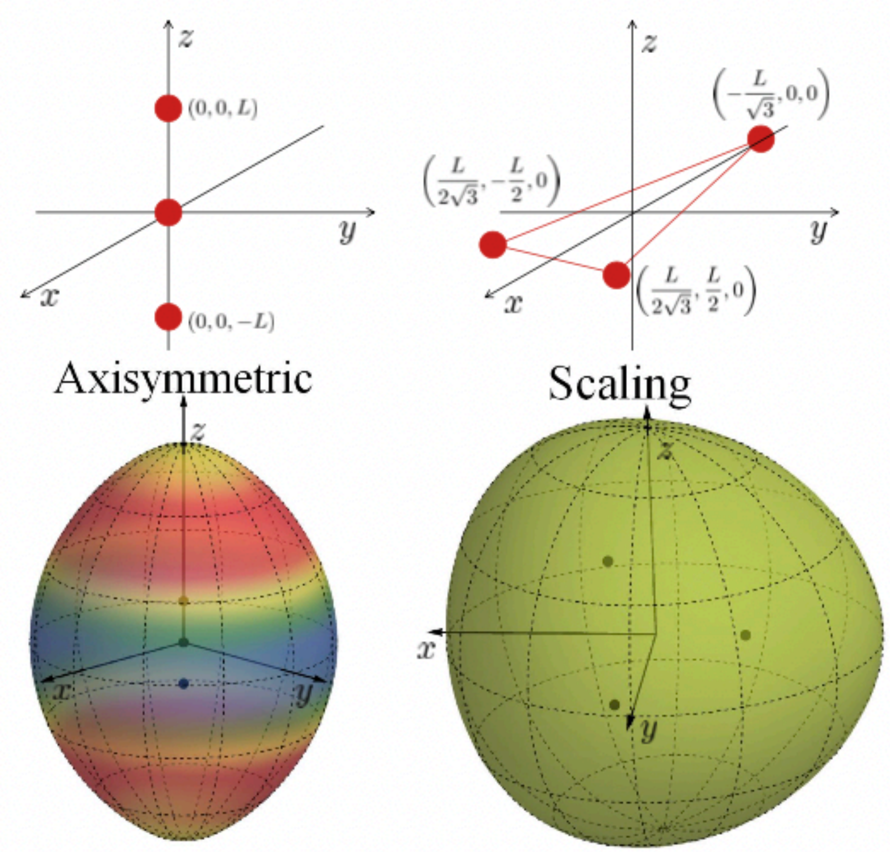


microstate geometry

$$ds^2 = -e^{2U}(dt^2 + \omega)^2 + e^{-2U}\delta_{ij}dx^i dx^j$$

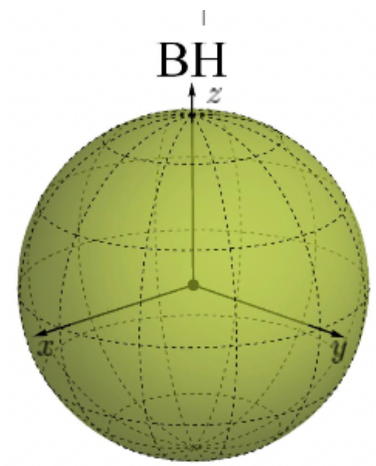
$$e^{2U}, \omega = \cdots$$

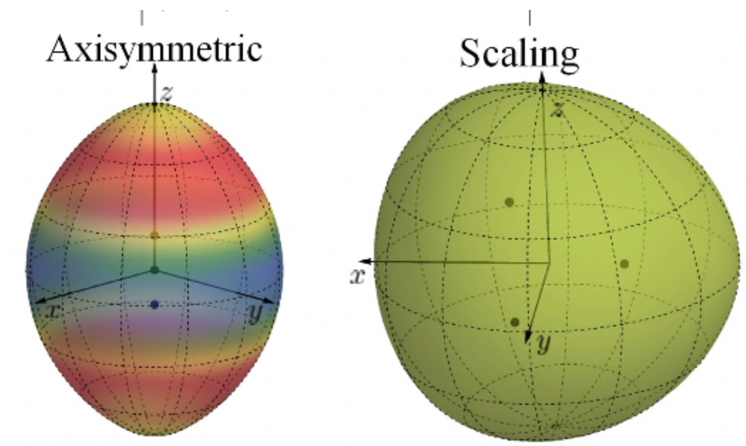
3-center geometry



What we want to do

- What is the typical gravitational waves from Fuzzball ?
- How different they are from corresponding BH ?
  - $\Box \Phi = 0 \longrightarrow$ ring down? echos ? QNM ?





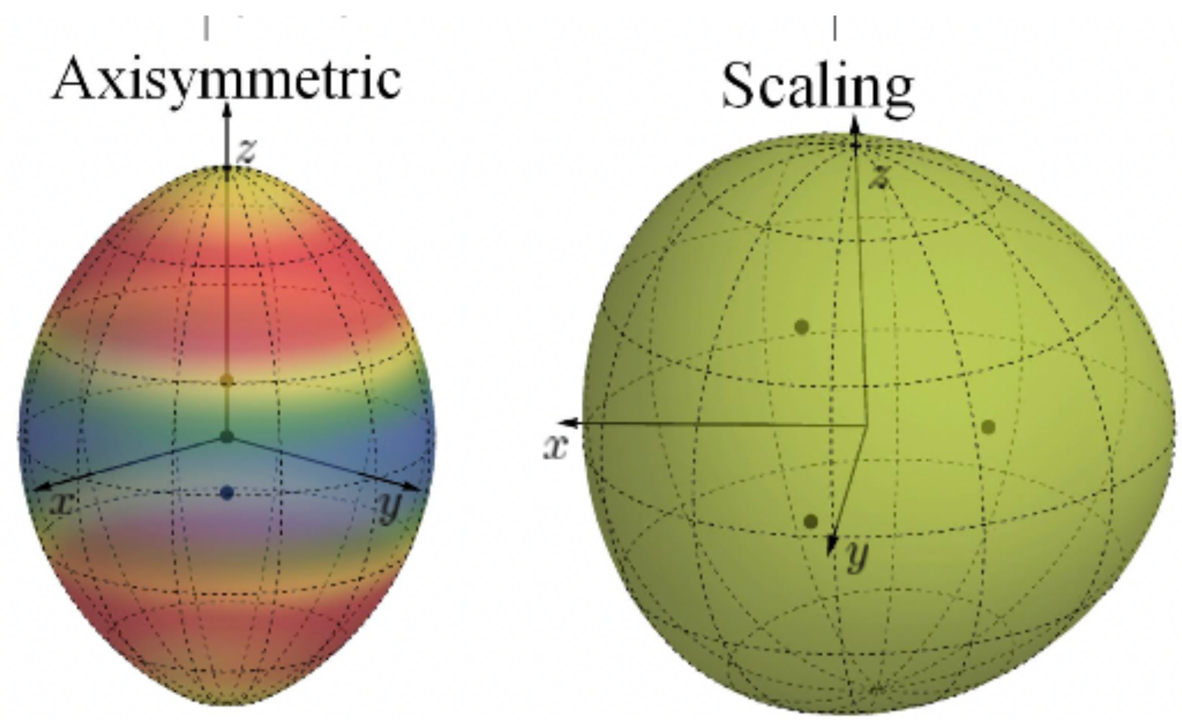
Spherical symmetry

- WKB approximation
- 1+1 time evolution
- direct integration

- WKB approximation
- 3+1 numerical simulation

QNM of 4 charge BH $\longleftrightarrow$ ringdown, echo, QNM (?)

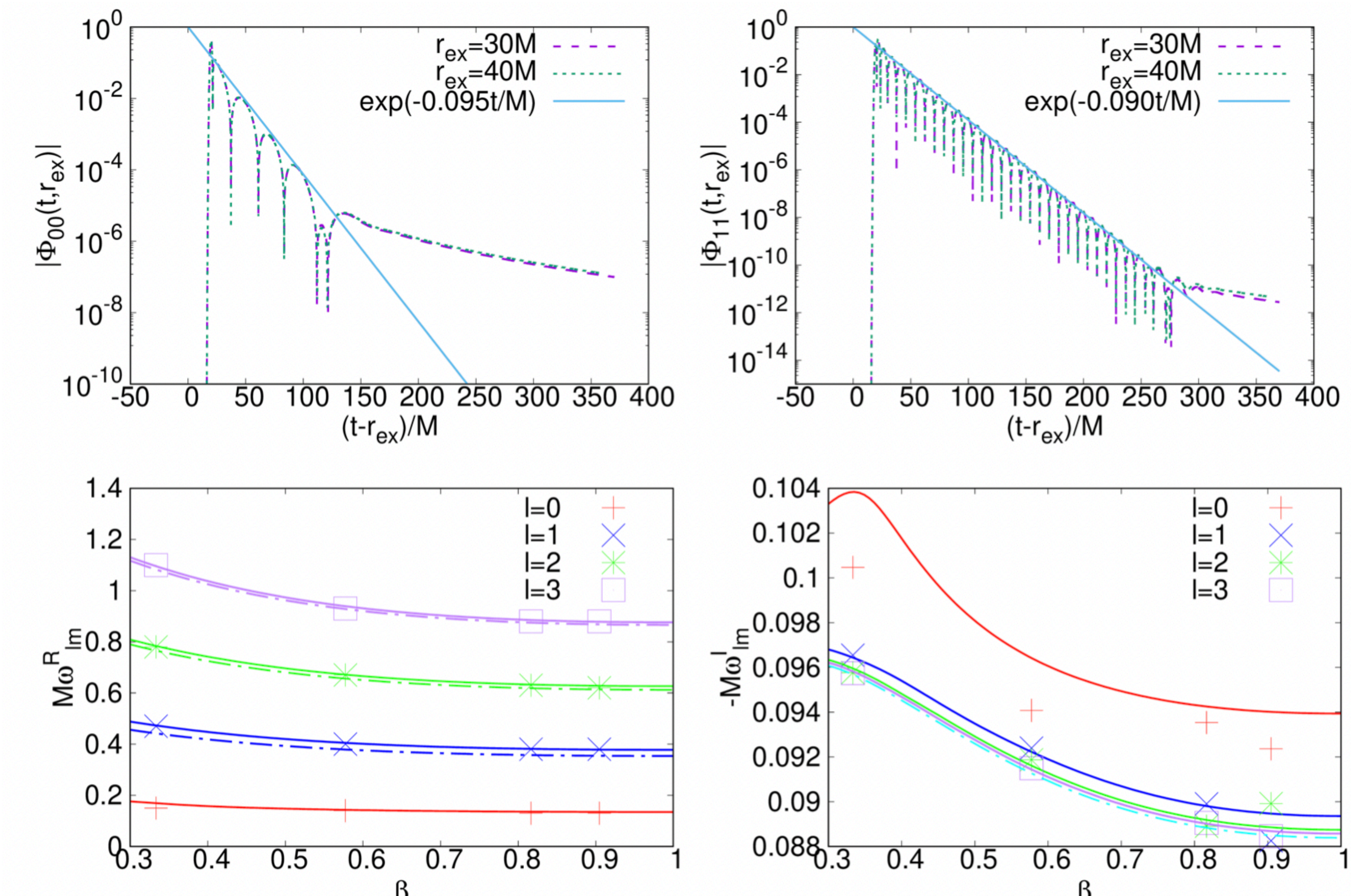
BH



Fuzzball

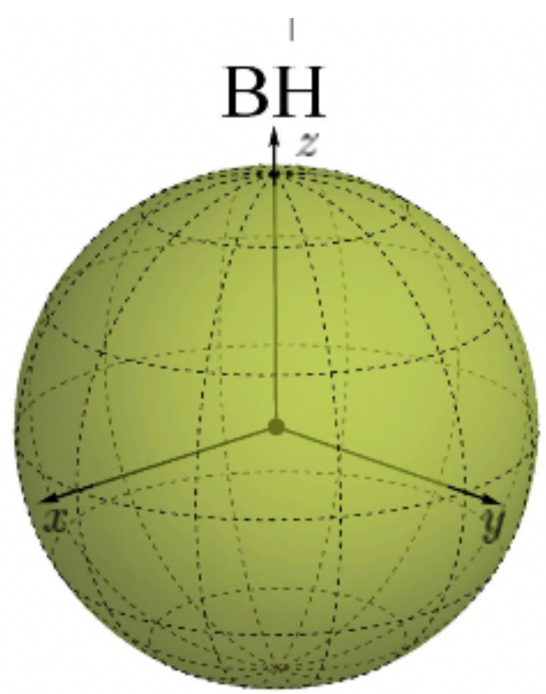
QNM in 4 charge BH

$$\beta = \sqrt{Q_2/Q_1}, Q_1 = Q_3, Q_2 = Q_4$$

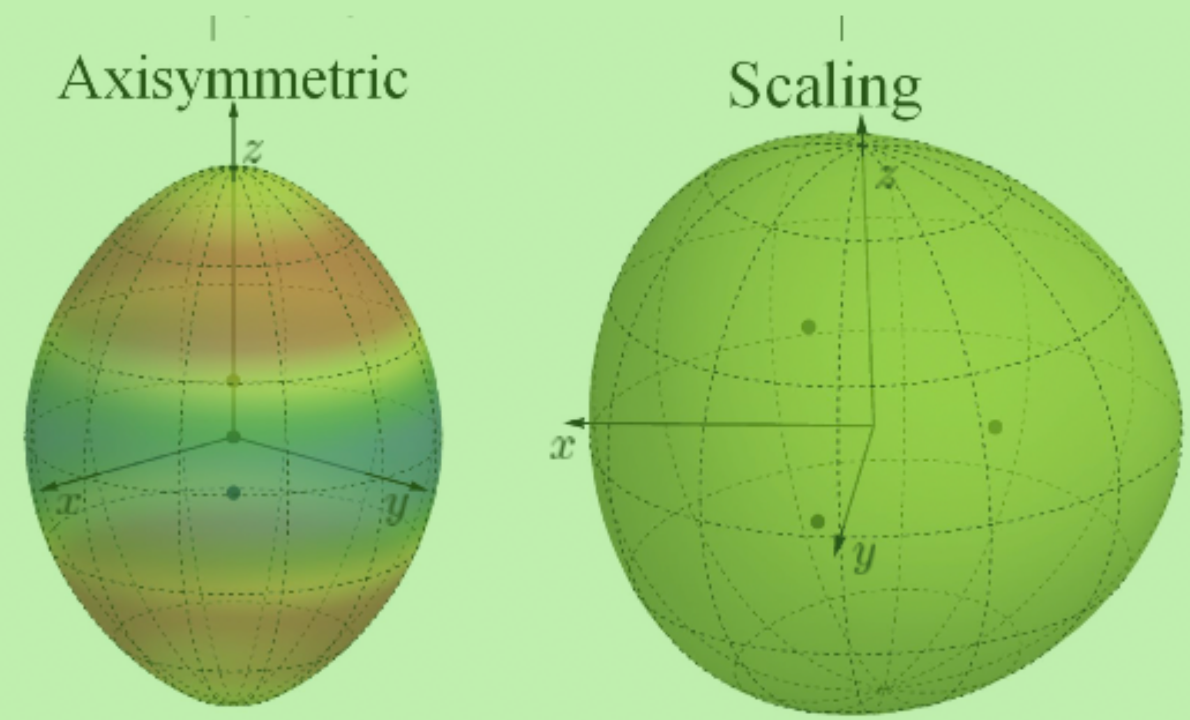


solid line : direct int
dot-dashed line : WKB

$$\omega_I M \sim \mathcal{O}(0.1)$$



BH



Fuzzball

Photon sphere around Fuzzball

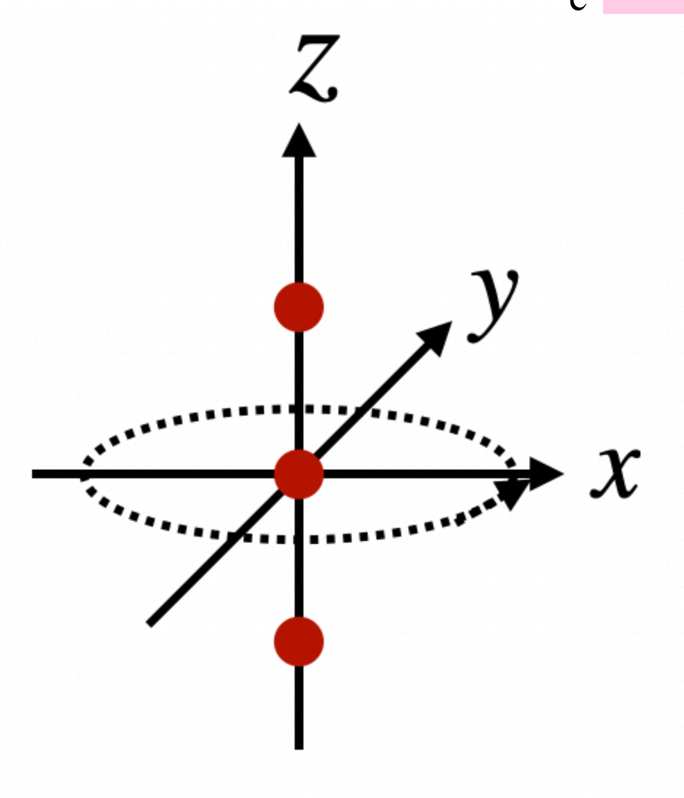
- WKB approximation
  - The unstable photon sphere in axisymmetric fuzzball.

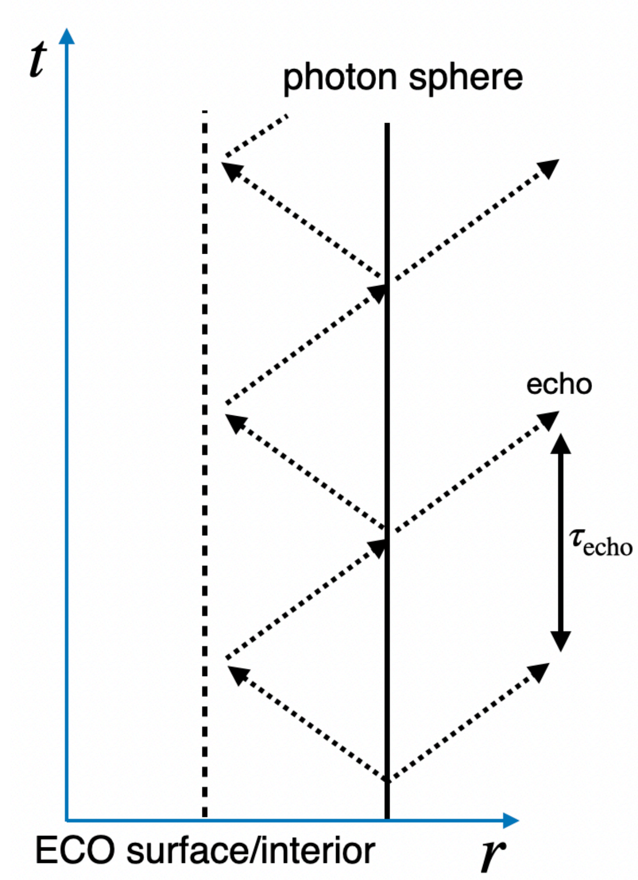
$$\mathrm{Re}\left(\omega_{\mathrm{QNM}}\right) \quad \longleftrightarrow \quad \text{orbital frequency}$$

$$\mathrm{Im}\left(\omega_{\mathrm{QNM}}\right) \quad \longleftrightarrow \quad \text{Lyapunov exponent}$$

  - echo time scale

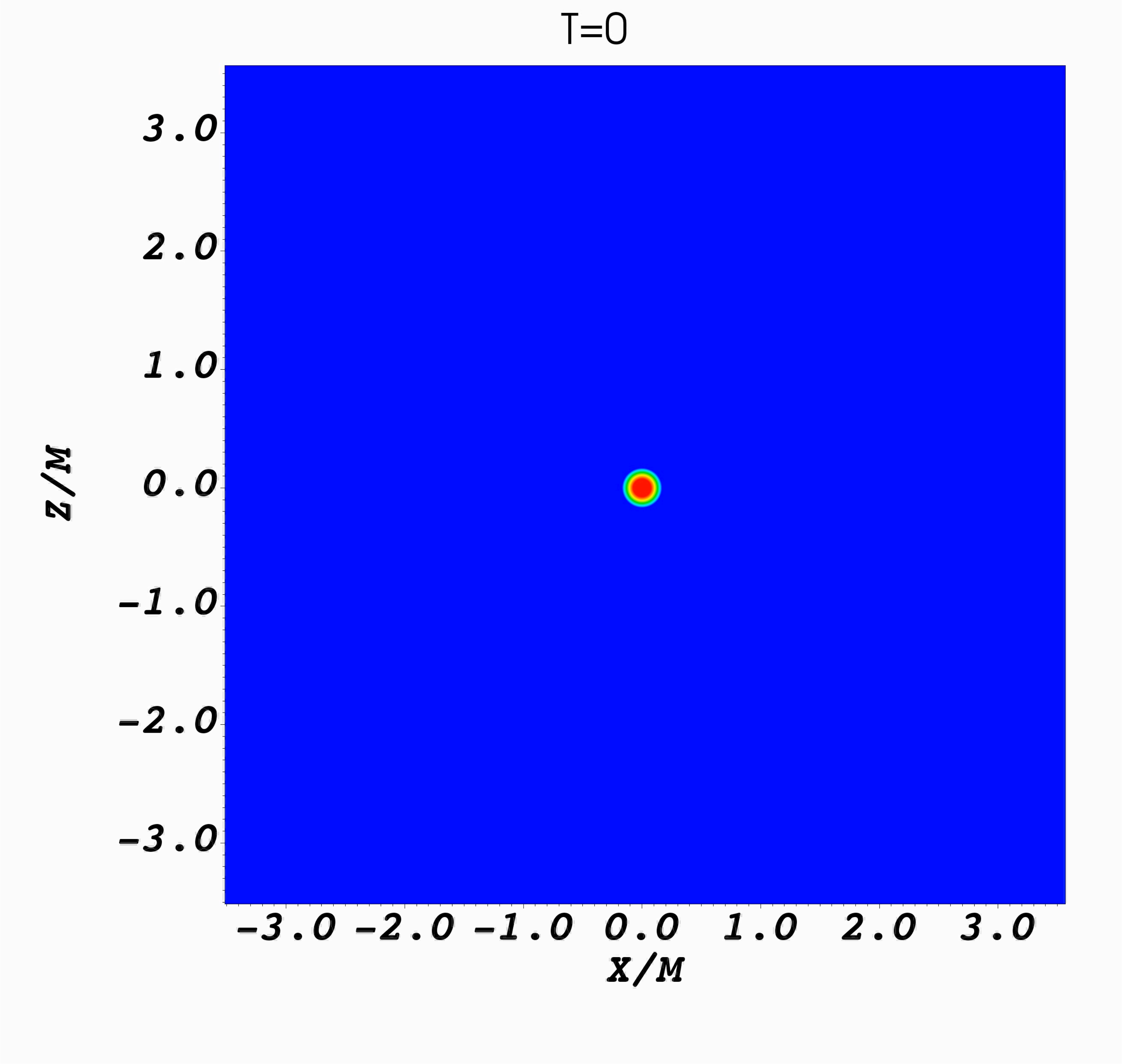
$$\tau_{\mathrm{echo}} = 2\int_{r_{\mathrm{c}}}^{r_{\mathrm{t}}} \frac{dr}{dr/dt}$$





3+1 simulations

- Axisymmetric Fuzzball

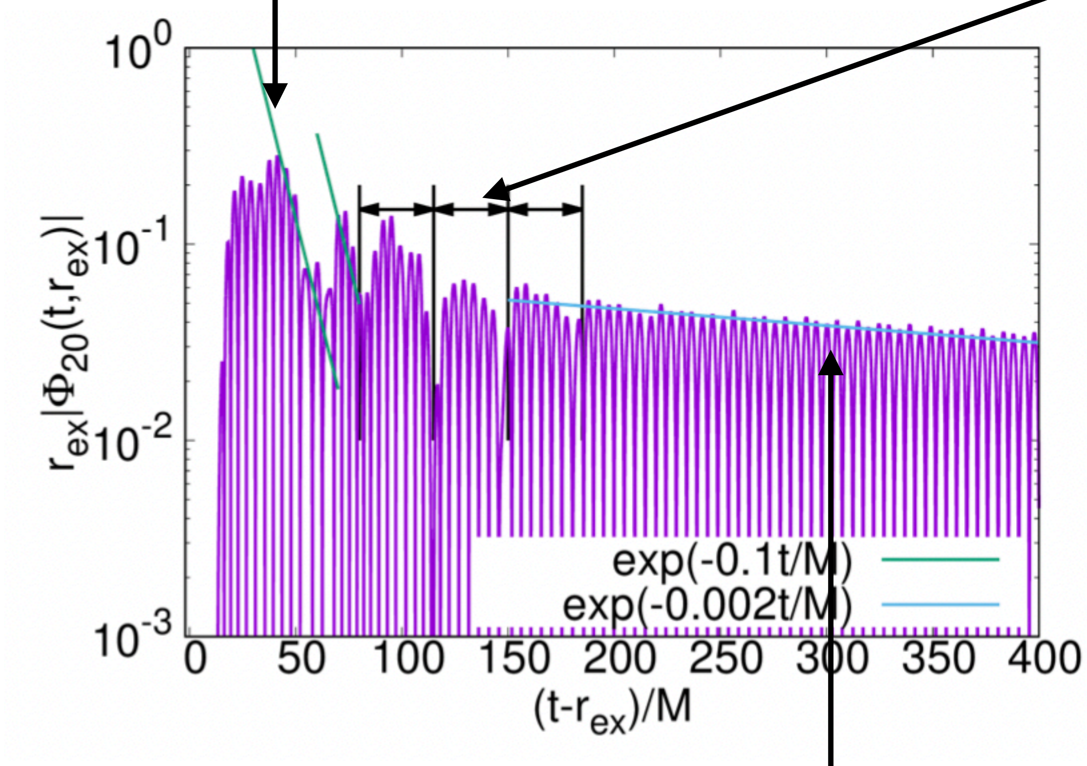


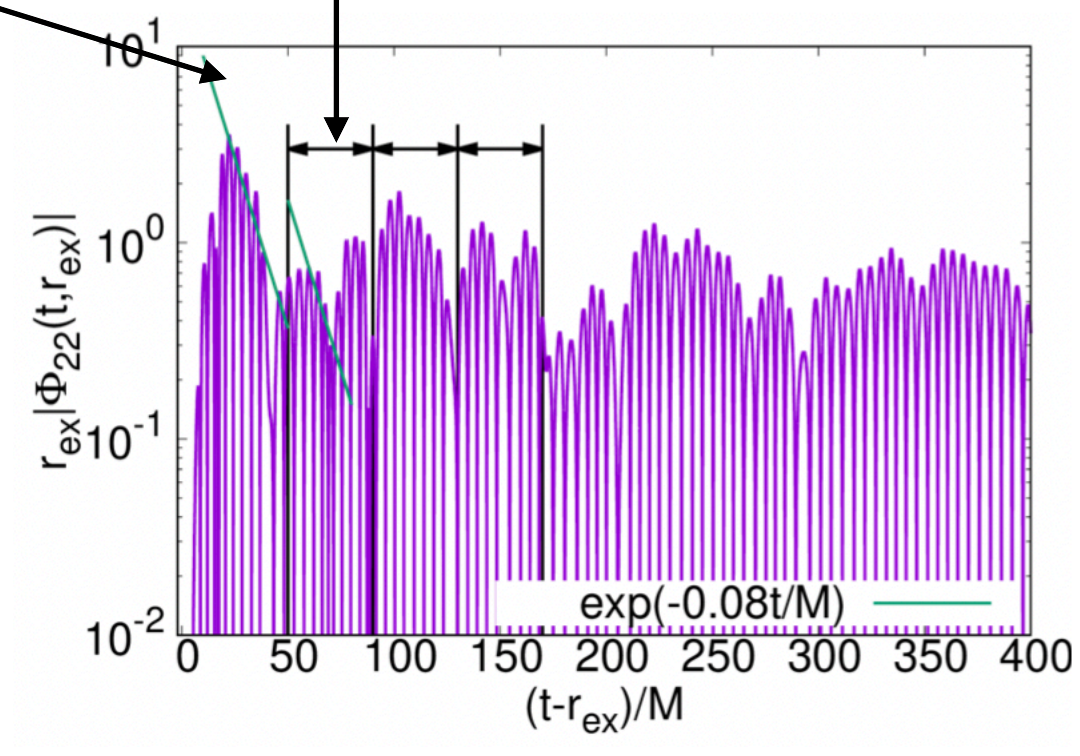
Waveform from Axisymmetric FB

This ringdown is same as QNM of corresponding BHs.

ringdown associated with photon sphere

τ_{echo}

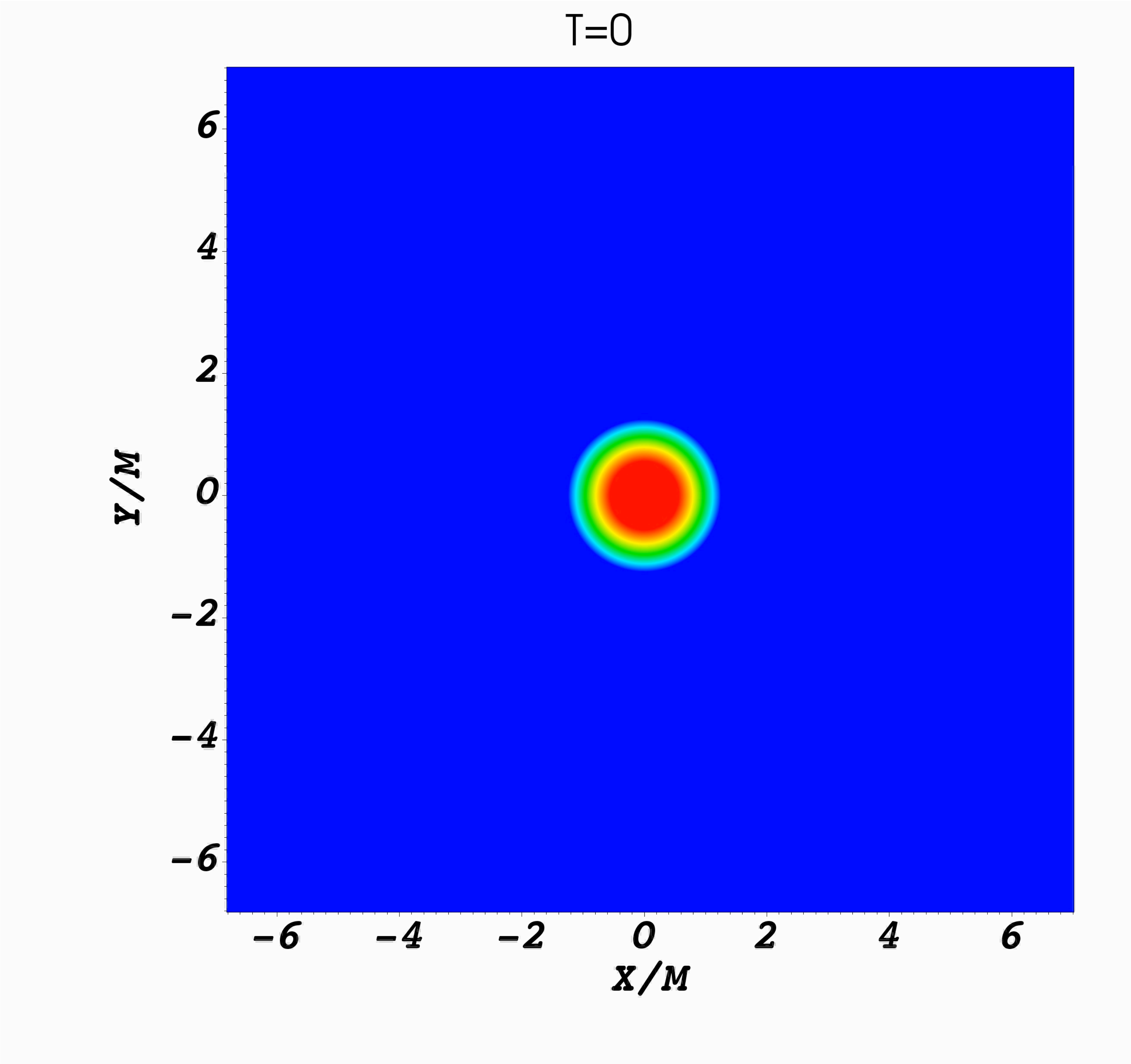




QNM of Fuzzball

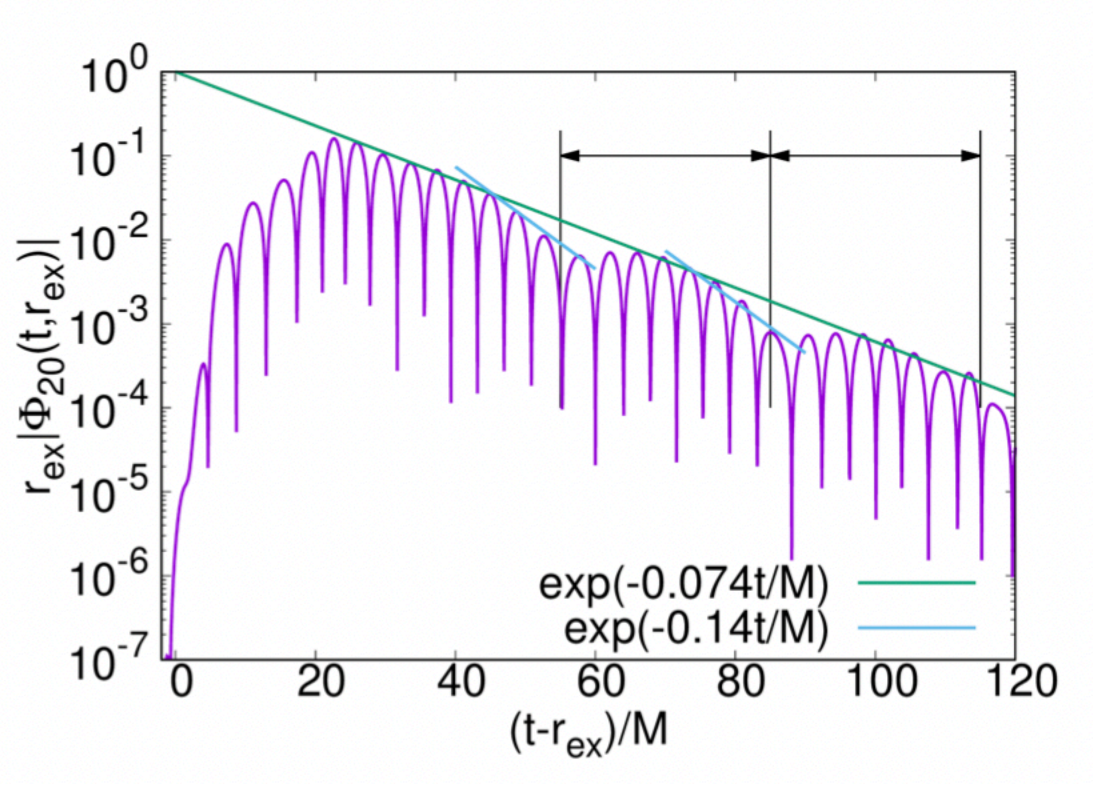
3+1 simulations

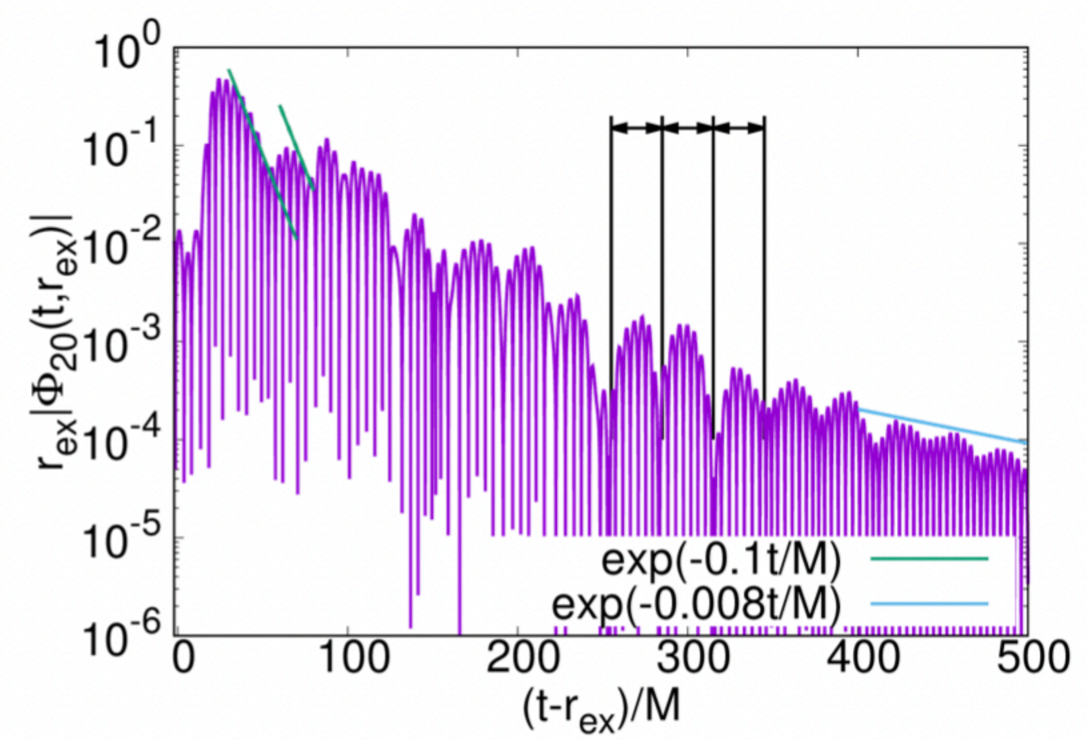
- Scaling Fuzzball



Waveform from Scaling FB

- We obtained the similar behavior around scaling fuzzball.

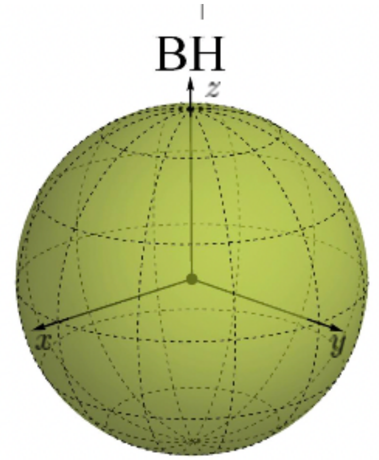




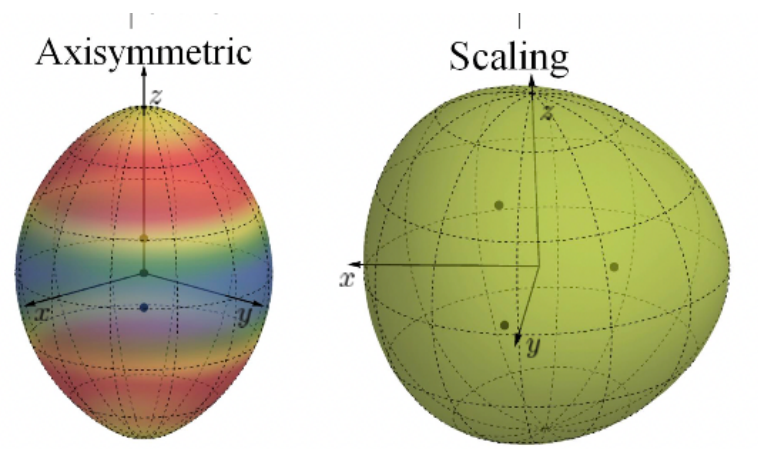
Summary

- We compared waveform from Fuzzball with waveform corresponding BH.

4 charge BH



Fuzzball



- ringdown ⟷ QNM of 4 charge BH
- echoes ⟷ WKB approximation (in axisymmetric FB)
- QNM of fuzzball

END